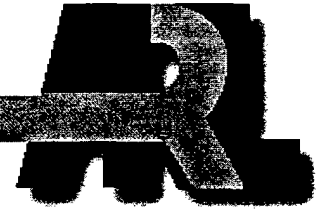ARMY RESEARCH LABORATORY

A Comparison of the Mobile Detection Assessment Reconnaissance System (MDARS) and Experimental Unmanned Vehicle (XUV) Robotic Vehicle Models

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A Comparison of the Mobile Detection Assessment Reconnaissance System (MDARS) and Experimental Unmanned Vehicle (XUV) Robotic Vehicle Models

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Abstract

During fiscal years 1997 and 1998, the Weapons Analysis Branch, Ballistics and Weapons Concepts Division, Weapons and Materials Research Directorate of the U.S. Army Research Laboratory, built an engineering-level model of the unmanned ground vehicle platform used in the Office of the Secretary of Defense Demo III robotics program. The computer model was a representation of the mobile detection assessment reconnaissance system (MDARS) chassis-suspension system. The model was developed within the structure of the combat vehicle engineering simulation (CVES). This effort was undertaken to develop a simulation tool to evaluate the "ride quality" of small robotic vehicle platforms during off-road travel. "Ride quality" is defined as the ability of the vehicle's suspension to attenuate shock and vibration between the terrain surface and the vehicle chassis.

An ensuing effort was undertaken to develop a computer model of the second generation Demo III robotic vehicle, the experimental unmanned vehicle (XUV). This model was developed with engineering parameters and data provided by the vehicle's manufacturer within the structure of CVES. A simulated ride quality comparison study was performed on the MDARS and XUV chassis-suspension models. The two models were exercised over three different types of simulated terrain and five different speeds. The terrain types were digital representations of the Aberdeen Test Center 2-inch washboard course and 3-inch bump course and the Waterways Experimental Station (Vicksburg, Mississippi) T101 course. The data used for the comparisons were chassis pitch rates and vertical accelerations.

The results showed that the XUV model provided substantial reductions in pitch rate and vertical acceleration amplitudes when compared to the MDARS model over most terrain types at all speeds. Since these robotic vehicles perform autonomous driving, any reduction in pitch rate and vertical acceleration is desirable because of their adverse effects on the driving sensors.

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A COMPARISON OF THE MOBILE DETECTION ASSESSMENT RECONNAISSANCE SYSTEM (MDARS) AND EXPERIMENTAL UNMANNED VEHICLE (XUV) ROBOTIC VEHICLE MODELS

1. Introduction

The Weapons Analysis Branch, Ballistics and Weapons Concepts Division, Weapons and Materials Research Directorate of the U.S. Army Research Laboratory (ARL) built an engineering-level model of the unmanned ground vehicle (UGV) platform used in the Office of the Secretary of Defense Demo III robotics program during fiscal years 1997 and 1998. The model was developed as a tool for analyzing small vehicle off-road mobility and chassis dynamics. The intended role of the autonomous robotic vehicle was to be a technology demonstrator to assess the possibility of an unmanned vehicle performing the Armor scout mission. The unaided vehicle would travel ahead of the troop section and would provide scout reconnaissance without the need for placing a human in a hostile environment. The vehicle platform used as the UGV was the mobile detection, assessment, and response system (MDARS), which was designed and built by Robotics Systems Technology (RST) of Westminster, Maryland. The MDARS vehicle was chosen since the vehicle platform was already built under an existing program for the U.S. Army Physical Security Equipment Management Office, Fort Belvoir, Virginia, as an external warehouse security robot. MDARS is a small, four-wheeled, Ackerman-steered autonomous vehicle, which is approximately 7 feet long, 4 feet wide, and 3 feet high; it weighs 1,700 pounds. The vehicle employs a 3-cylinder, 23-horsepower diesel engine that powers a four-wheel hydraulic drive system. The MDARS vehicle is shown in Figure 1.

Figure 1. The MDARS Vehicle.

In fiscal year 1999, an ensuing contract to build a second generation robotic vehicle platform was awarded to General Dynamics Robotic Systems (GDRS) (formerly RST) to build the experimental unmanned vehicle (XUV). This is an all-wheel-drive autonomous vehicle with Ackerman steering, which is approximately 10 feet long, 5 feet wide, 4 feet high and has a curb weight of ~2,800 pounds. The XUV uses a 4-cylinder, 78-horsepower diesel engine that powers a four-wheel hydraulic drive system. A computer model of the XUV was subsequently developed as a further extension of the modeling tools used for analyzing small vehicle off-road mobility and chassis dynamics. The XUV is shown in Figure 2.
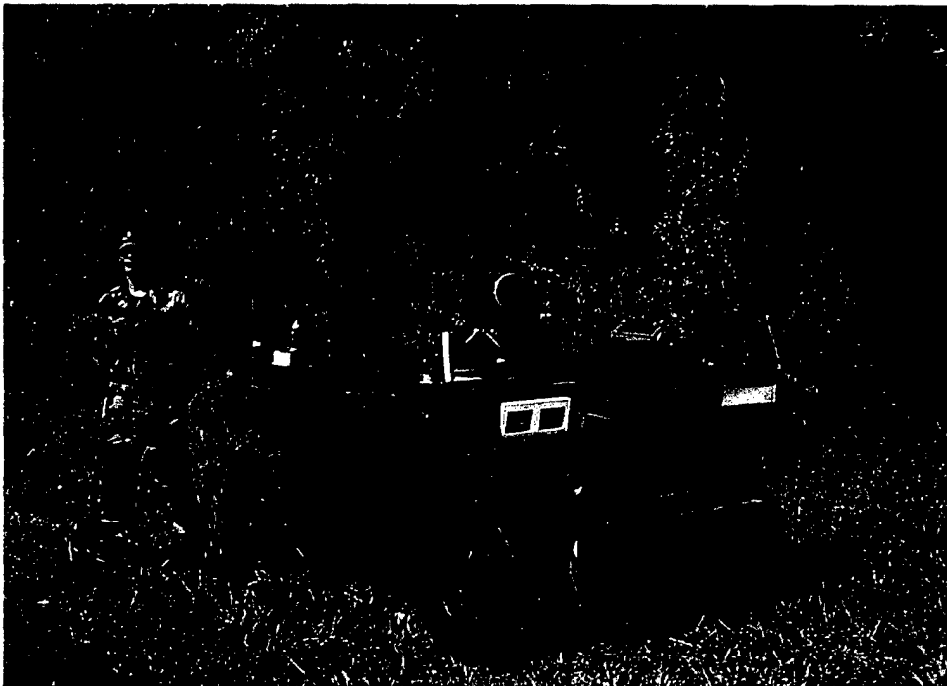
Figure 2. The XUV.

The MDARS vehicle and XUV were both modeled within the structure of ARL's combat vehicle engineering simulation (CVES). CVES contains detailed engineering models of the chassis-suspension system, the fire control system, and the gunner for both the Abrams M1A1 combat tank and the A3 version of the Bradley fighting vehicle system. The MDARS and XUV automotive chassis models were developed with the chassis-suspension model that resides in CVES. The CVES chassis-suspension model is a six-degree-of-freedom engineering-level model that employs detailed vehicle data and parameters to accurately compute vehicle chassis-suspension motion. Vehicle parameters for the MDARS were supplied by GDARS and by the Aberdeen Test Center (ATC). Parameters for the XUV were supplied by GDRS solely. ATC performed static testing on the MDARS vehicle to obtain engineering data for input to the CVES chassis-suspension model. The XUV has not been measured or tested by ATC.

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The MDARS model has been validated against dynamic test data collected by ATC and documented in Fazio (1999). Upon completion of the XUV model, the MDARS and XUV models were exercised and compared within CVES via digital terrain profiles that simulated actual terrain. The data used for the model comparison were chassis pitch rates and chassis vertical accelerations. The simulation time history output for the two models was then compared to evaluate the differences in ride quality. "Ride quality" is loosely defined as the ability of a vehicle's suspension to attenuate shock and vibration between the terrain surface and the vehicle chassis. In other words, "How well does the suspension smooth the bumps?"

Creation of the MDARS model provided ARL with a tool to evaluate engineering-level concepts for small vehicle platforms. This effort has been extended to include modeling of the XUV, which represents the ongoing evolution of the Demo III robotic vehicle. Further, as sensor systems were developed for small vehicle platforms, models representing these systems (namely, the Stabilized Sensor Platform model) have been incorporated into the vehicle model via the fire control module that resides in CVES.

2. Procedures

2.1 Modeling the Vehicles

The author began modeling the MDARS and XUV by using the chassis-suspension model from the CVES code. The chassis-suspension model describes a vehicle in terms of the equations of motion associated with movement of the vehicle's tires, wheels, and chassis. An external disturbance (terrain input and bumps) is applied to the vehicle's tires, which deflects the tire, thus producing a force on the vehicle's wheel and hub assembly. Forces from the vehicle's suspension are also applied to the wheel and hub assembly. The sum of these forces generates a wheel acceleration that is numerically integrated to produce wheel rate and is integrated again to produce wheel position. The wheel position and chassis position produce a spring deflection, which creates a force acting on the vehicle chassis. Wheel rate and chassis rate are combined to produce a suspension rate, which produces a damping force that also acts on the vehicle chassis. The suspension forces generate chassis linear accelerations, which are numerically integrated to produce chassis linear rates and positions. The suspension forces also generate chassis torques about the vehicle's center of gravity (c.g.). The chassis torques create angular accelerations that are numerically integrated to produce angular rates and positions. These motions are calculated for each tire-wheel-suspension assembly that is attached to the vehicle. The simulated terrain elevations and elevation rates of change are applied to each individual tire-wheel-suspension assembly. The simulation is

configured so that the terrain that passes beneath the left and right side tires can be the same or (to add further realism to the simulation) can be shifted to allow different terrain elevations and elevation rates to "arrive" beneath the left and right side wheel sets. This terrain-shifting feature adds a roll component to the vehicle chassis. Future work will include individual terrain data sets for each individual tire-wheel-suspension assembly.

2.1.1 MDARS and XUV Chassis-Suspension Data and Parameters

Although MDARS engineering data and vehicle parameters used within the model came from a number of sources, most were supplied by GDRS and ATC. GDRS solely supplied all the engineering data and vehicle parameters for the XUV. Data about certain subsystems and components, such as dampers (shock absorbers) and tires, were acquired from the component manufacturers. GDRS supplied detailed engineering information pertaining to the design of the MDARS and XUV such as physical placement of spring and damper assemblies, lengths of control arms, and turning angle of the wheels. ATC performed numerous static tests on the MDARS vehicle to determine the physical characteristics. The tests included weighing the total platform and weighing the individual suspension components to ascertain sprung and unsprung masses, weight distribution, centers of gravity, and moments of inertia, spring force versus deflection curves, tire spring force versus deflection curves, and general vehicle dimensions. The tire manufacturer[1] also supplied tire spring force versus deflection curves, which were used to validate ATC's physical test of the vehicle's tires. However, the manufacturer was unable to supply data about the tire's damping characteristics. Therefore, a standardized value acquired from the U.S. Army Tank-Automotive Command was used within the MDARS tire model instead. Because availability of the vehicle was limited, no static testing was performed by ATC on the XUV to determine its physical characteristics. All the physical characteristics of the XUV were provided by GDRS. These data are shown in Table 1.

Damper force versus velocity curves were acquired from the damper manufacturers[2]. Curves for the MDARS suspension spring force, suspension damping force, and tire spring force are shown in Figures 3, 4, and 5, respectively.

Curves for the XUV suspension spring force, suspension damping force, and tire spring force are shown in Figures 6, 7, and 8, respectively.

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[1] Dico Tire, Inc.
[2] AVO (not an acronym) Shocks USA, Inc.

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Table 1. MDARS and XUV Physical Characteristics

| Parameter	MDARS	XUV	Unit
Roll Moment of Inertia	105	230	Slug-ft^2
Yaw Moment of Inertia	245	707	Slug-ft^2
Pitch Moment of Inertia	226	558	Slug-ft^2
Curb Weight	1700	2500	Pounds
Unsprung Mass	11.49	9.94	Slugs
Vertical c.g.	17.1	20.0	Inches, above ground level
Lateral c.g.	0.0	0.0	Inches, to right of vehicle center line
Longitudinal c.g.	23.1	34.7	Inches, forward of rear axle center line
Length of Body	80.9	110.0	Inches
Width of Body	50.9	65.8	Inches
Height of Body	38.2	42.0	Inches
Length of Wheelbase	57.6	74.0	Inches
Width of Track	43.1	56.0	Inches
Front Weight Bias	40	47	Percent
Rear Weight Bias	60	53	Percent
Tire-Damping Coefficient	50	50	Lb-sec/ft
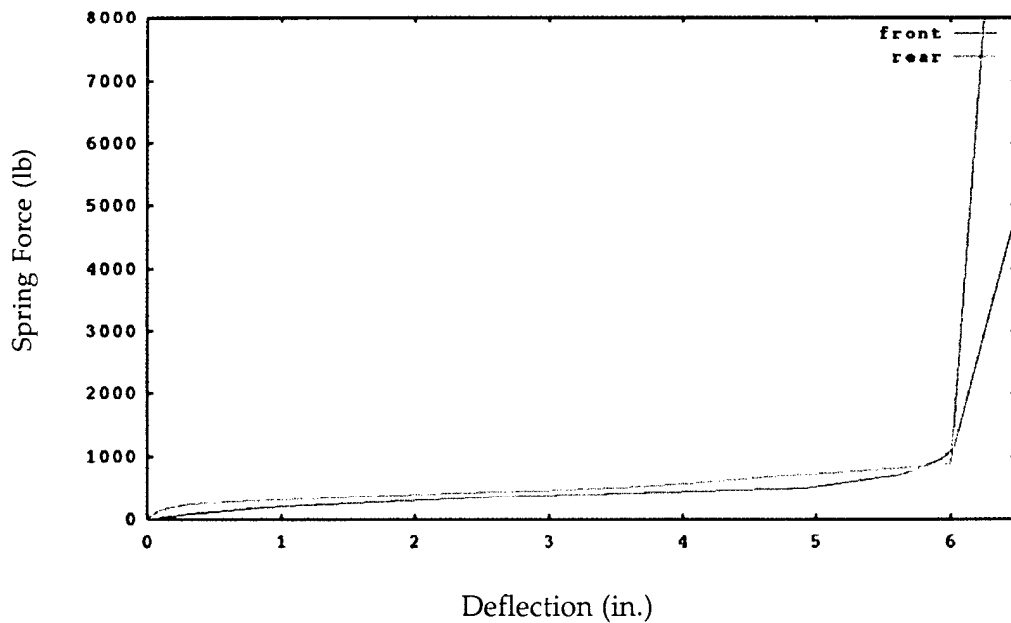
Figure 3. MDARS Spring Curves.
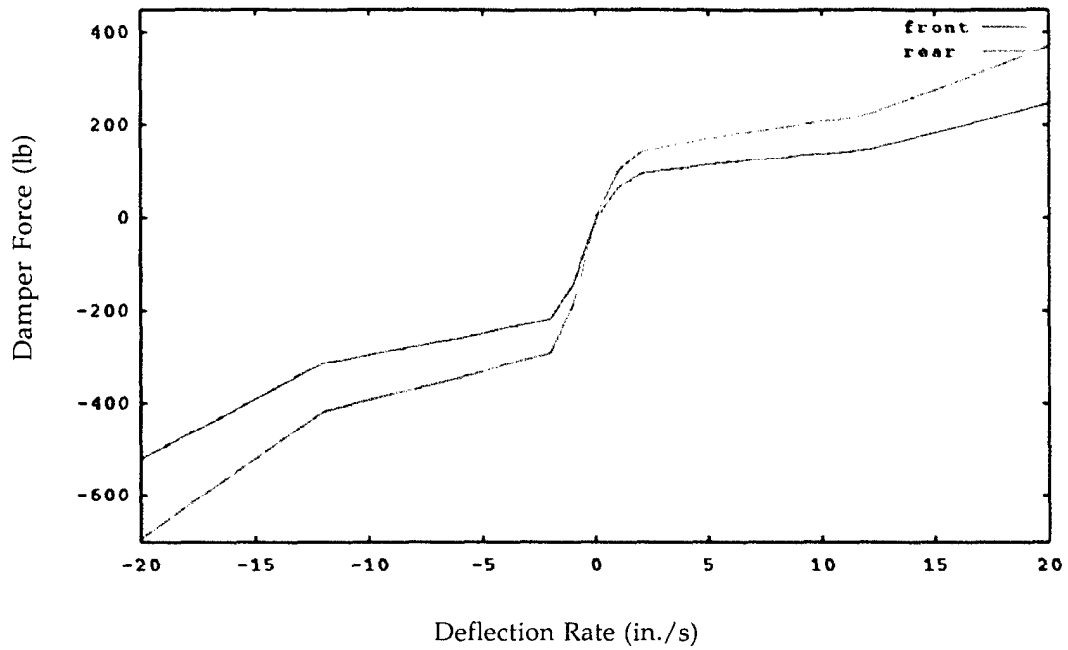
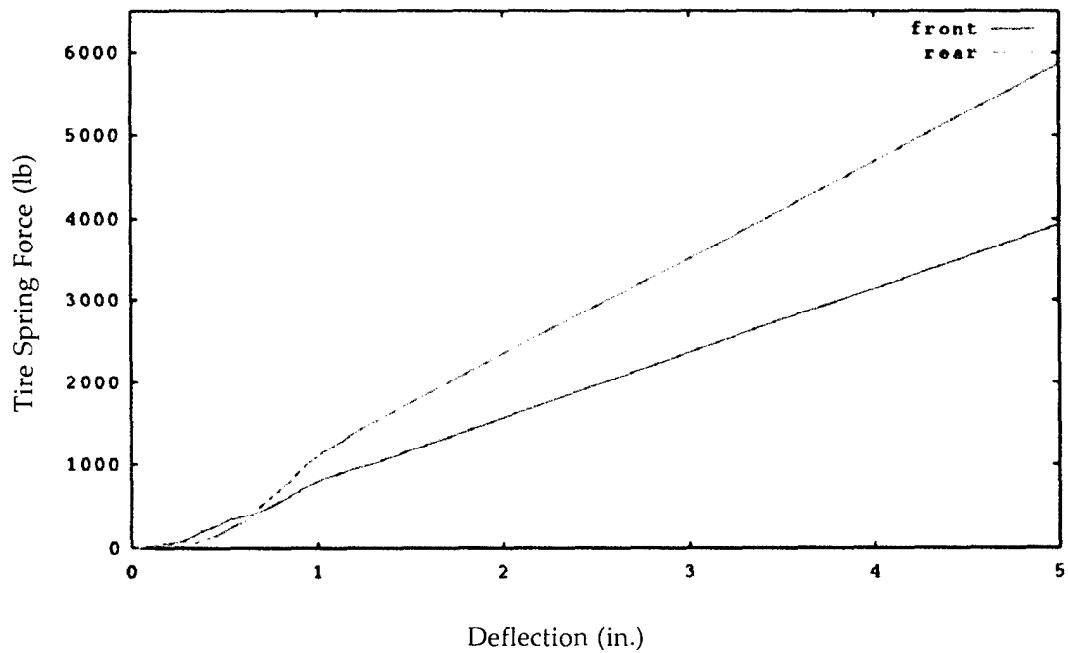Figure 4. MDARS Damper Curves.

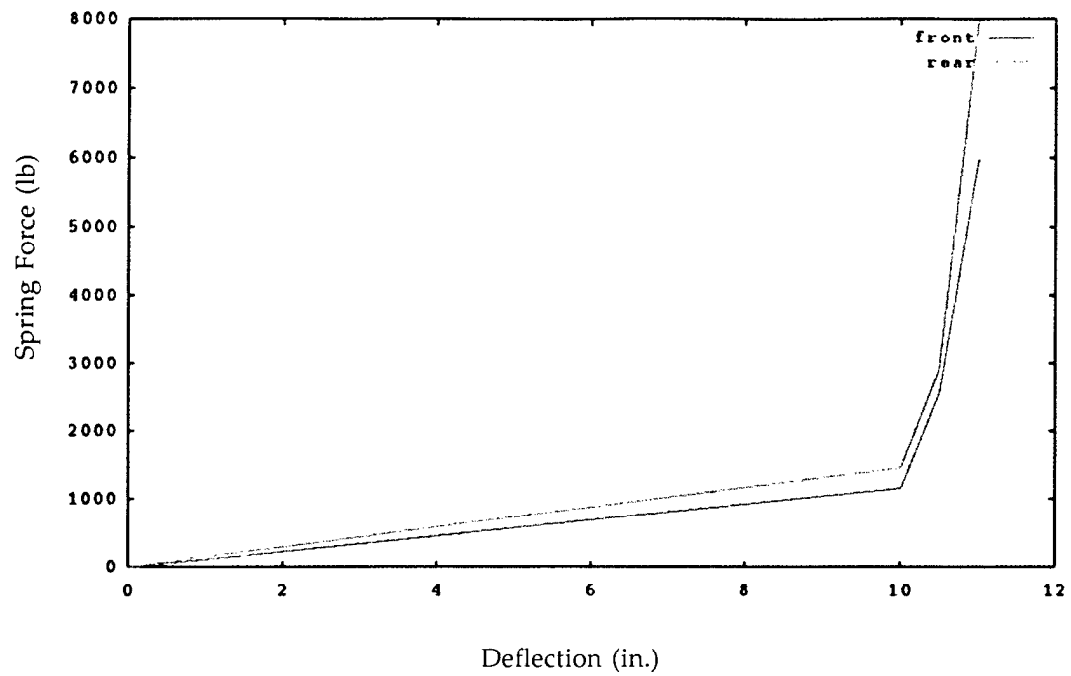Figure 5. MDARS Tire Spring Curves.
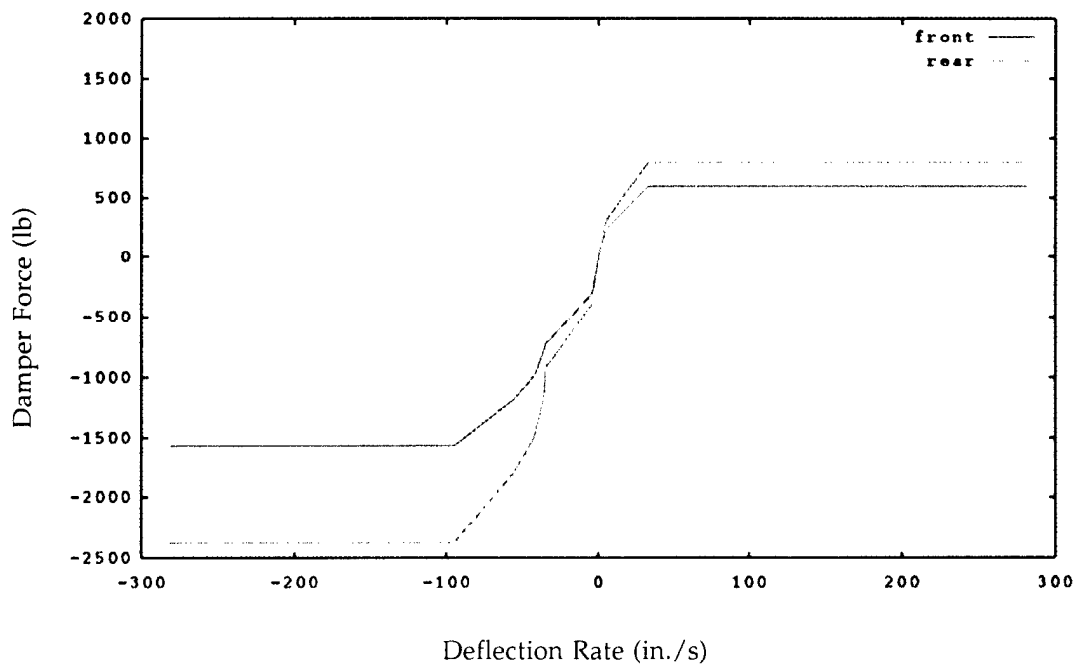
Figure 6. XUV Spring Curves.
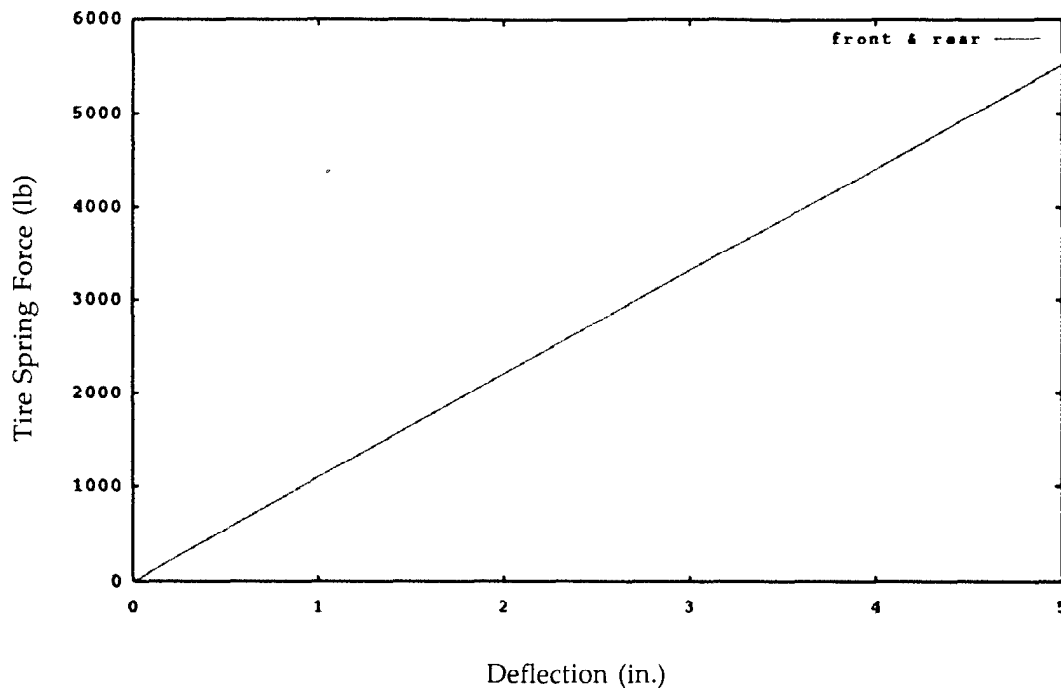

Figure 7. XUV Damper Curves.

Figure 8. XUV Tire Spring Curve.

2.2 Comparison of the MDARS and XUV Simulations

Three simulated terrain types and five speeds were selected for the comparison. The terrain types were digital representations of ATC's 2-inch washboard course and 3-inch bump course and Waterways Experimental Station (WES) (Vicksburg, Mississippi) T101 course. The selected vehicle speeds on these terrain types were 2, 4, 8, 12, and 18 mph. The WES T101 terrain was not traversed at speeds greater than 8 mph. The simulations were not compared at the speeds of 12 and 18 mph because certain sections of the T101 terrain would induce extremely high pitch rates and vertical accelerations in the MDARS vehicle. These high pitch rates and vertical accelerations are indications that the vehicle is being operated beyond its design limits. These speeds were chosen since they closely duplicated the test speeds used by ATC when dynamic testing was performed on the MDARS robotic vehicle. The 2-inch washboard course consists of a concrete track with a profile resembling a sine wave with a 24-inch wavelength and a 2-inch peak-to-peak amplitude. The 3-inch bump course is a concrete track with regularly spaced bumps approximately 30 feet apart. Some bumps are set perpendicular to the direction of travel, and others are set at varying oblique angles. The bump profile is a rounded section with a 3-inch maximum height and a 36-inch length. The digital representation of the 3-inch bump course included only those bumps that were set perpendicular to the direction of travel. The exclusion of the oblique bumps was an effort to decouple the chassis pitch and roll motions. The analysis was focused in the pitch plane, which has become an area of concern for small autonomous vehicles because of driving camera image instability problems from excessively high pitch rates. Thus, the simulated chassis pitch motions over the 3-inch bump course were

compared only when the vehicles encountered 3-inch bumps that were perpendicular to the direction of travel. The WES T101 course is a random terrain representing an off-road path with medium severity bump intensity, described statistically as having a 1.5-inch root mean square (rms) bump height. The MDARS and XUV simulations were run with the same test matrix, which included a representation of the 2-inch washboard course, the 3-inch bump course, and the WES T101 course. The data used for comparing the MDARS and XUV models were time histories of the chassis vertical acceleration and chassis pitch rate. The study matrix is summarized in Table 2.

Table 2. Study Matrix

Courses	Speeds (mph)				
	2	4	8	12	18
2-inch Washboard	yes	yes	yes	yes	yes
3-inch Bump	yes	yes	yes	yes	yes
WES T101	yes	yes	yes	no	no

3. Results

3.1   MDARS Versus XUV Traversing the 3-inch Bump Course

3.1.1 Pitch Rate Comparison

The MDARS and XUV models were run at the five speeds over the simulated 3-inch bump course. When the pitch rates of the two vehicles were compared while the vehicles traversed the 3-inch bump, the XUV model produced a slightly lower pitch rate amplitude as it moved at the slower speeds of 2 and 4 mph. Figures 9 and 10 show the 2- and 4-mph comparison, respectively.
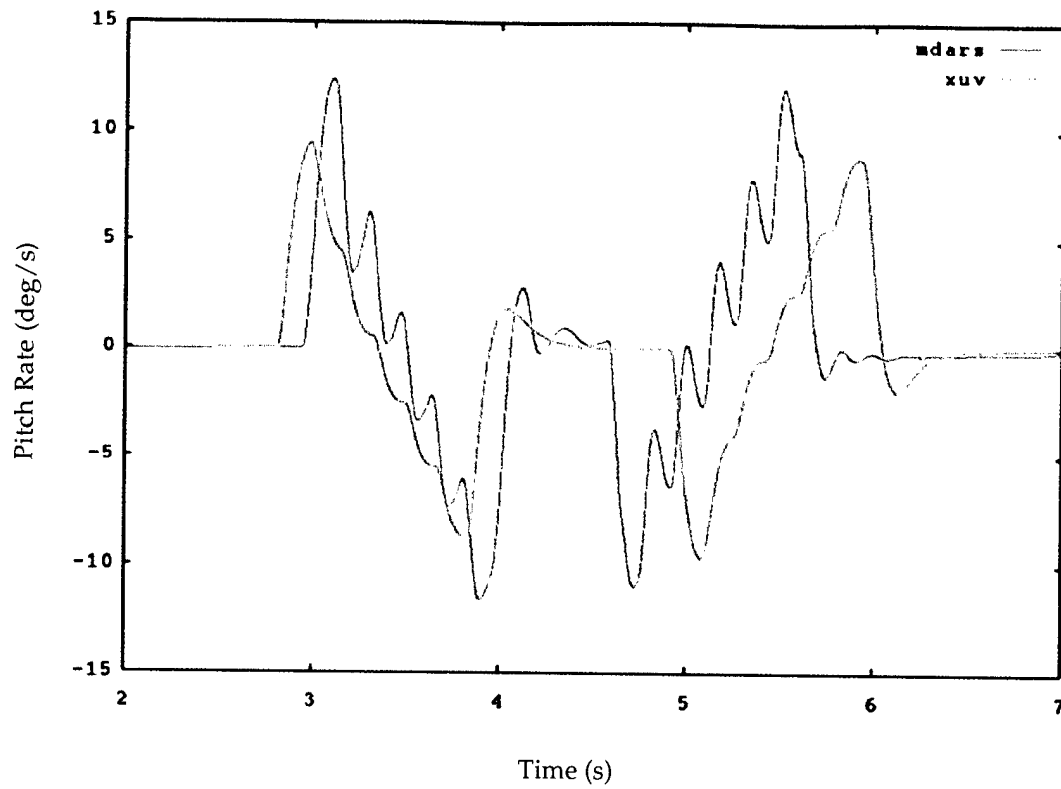
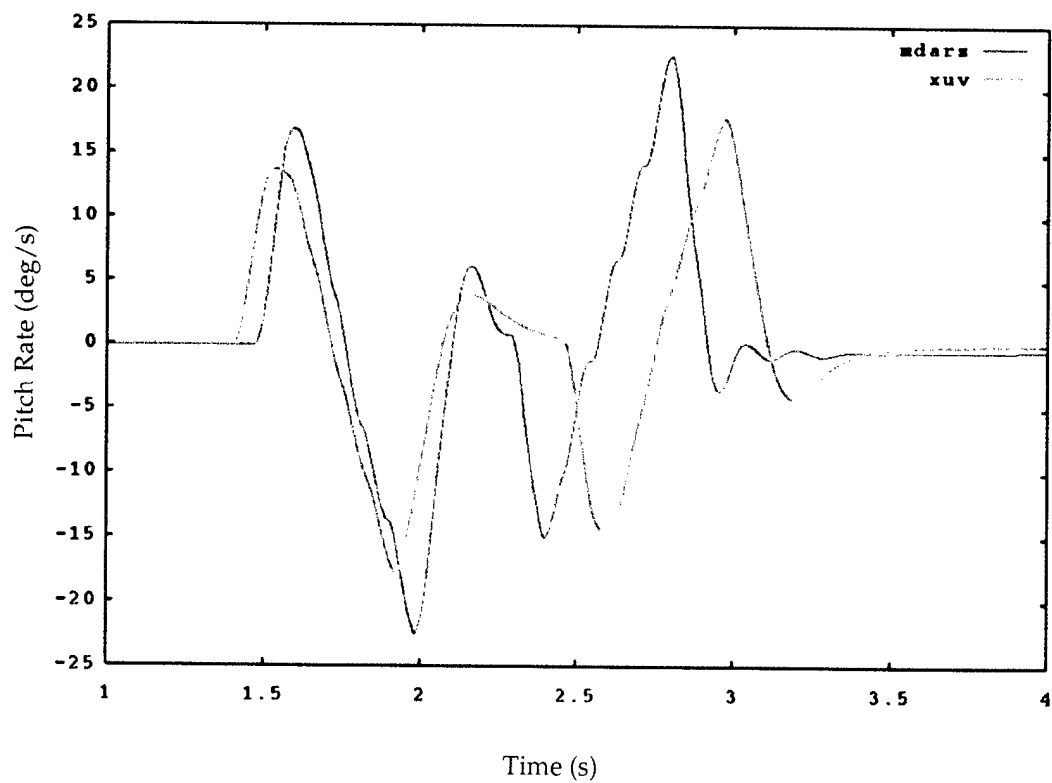Figure 9. Chassis Pitch Rate, 3-Inch Bump, 2 mph.

Figure 10. Chassis Pitch Rate, 3-Inch Bump, 4 mph.

When the MDARS and XUV models were compared while running at the speeds of 8 and 12 mph, the XUV produced a much lower pitch rate amplitude. The pitch rate amplitude is approximately 25% lower. The pitch rate amplitudes for the 8- and 12-mph comparisons are shown in Figures 11 and 12, respectively.
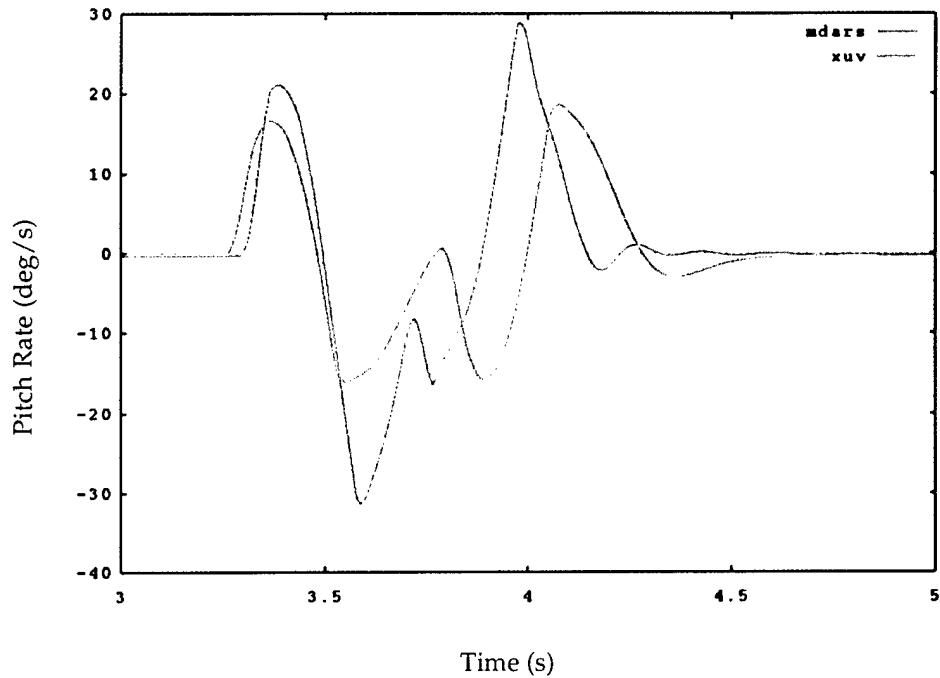

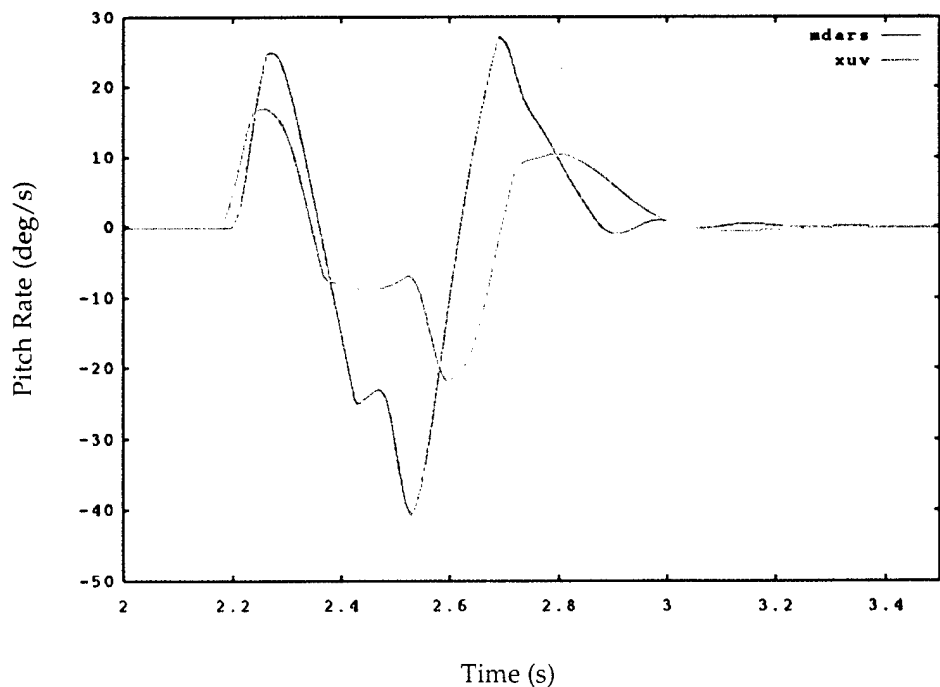Figure 11. Chassis Pitch Rate, 3-Inch Bump, 8 mph.

Figure 12. Chassis Pitch Rate, 3-Inch Bump, 12 mph.

Comparison of the models at the highest speed shows that the XUV produced a significantly lower pitch rate amplitude than the MDARS. The XUV model's pitch rate amplitudes are approximately 50% lower when the XUV ran at the 18-mph speed. The pitch rate comparison for the 18-mph run is shown in Figure 13.
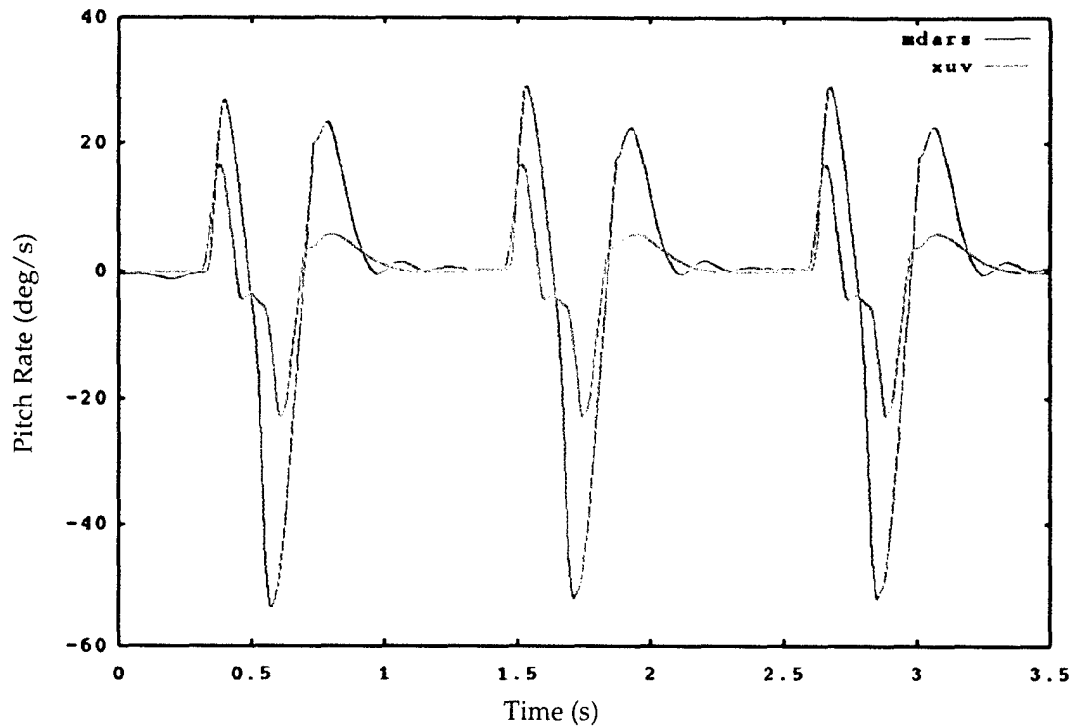

Figure 13. Chassis Pitch Rate, 3-inch bump, 18 mph.

3.1.2 Chassis Vertical Acceleration Comparison

The MDARS and XUV models were run over the 3-inch bump course at the five speeds, as noted previously in the pitch rate comparisons. Comparison of the chassis vertical accelerations of the MDARS and XUV models showed the same basic trends as did the pitch rate comparisons. Comparison of the lower speed runs, 2 and 4 mph, showed that the XUV model produced peak vertical acceleration amplitudes approximately 25% lower than those of the MDARS model. At these low speeds, peak vertical acceleration amplitudes for both models are quite low. Peak amplitudes below 0.25 g are shown in Figure 14, and peak amplitudes below 0.5 g are shown in Figure 15.
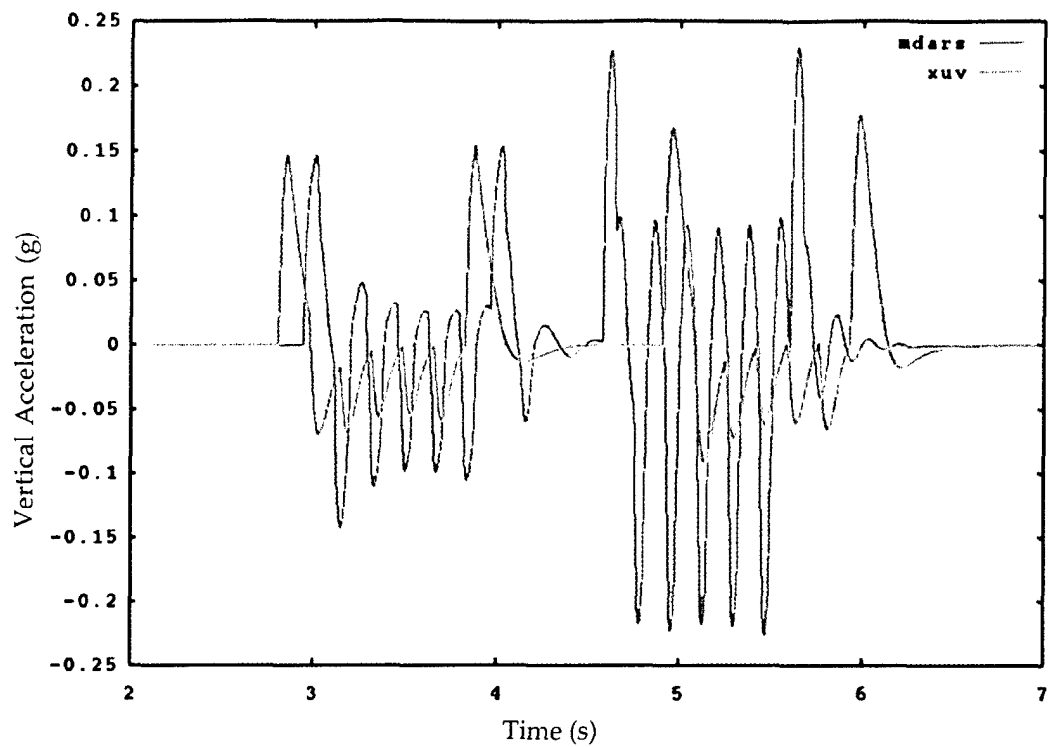
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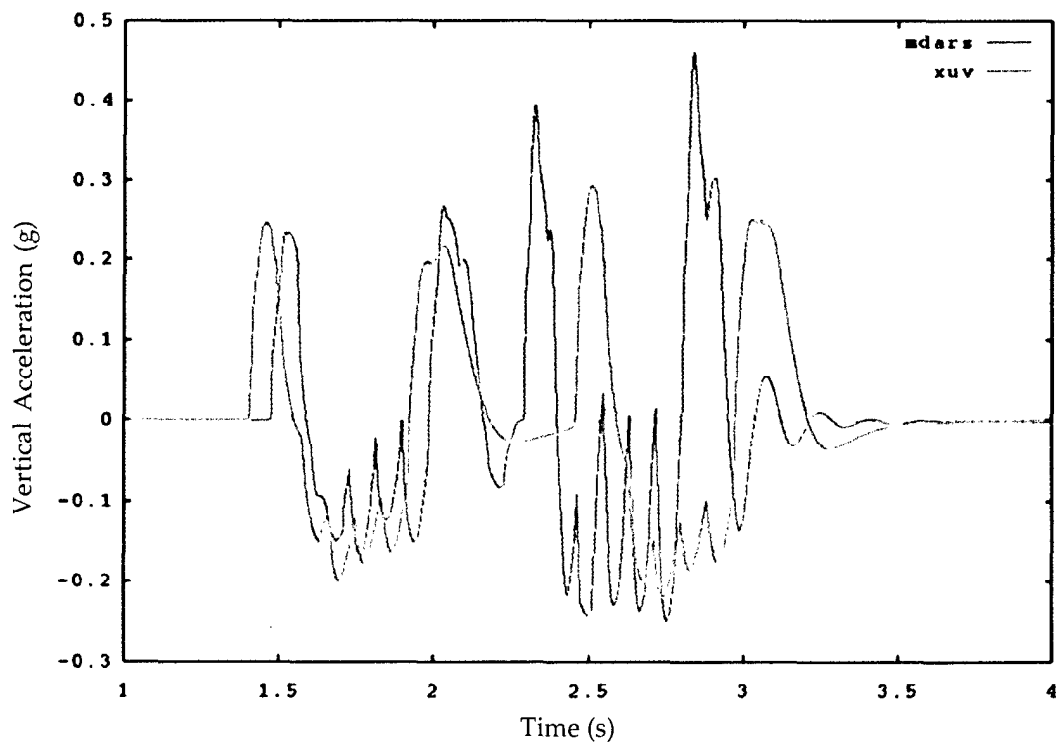Figure 14. Chassis Vertical Acceleration, 3-Inch Bump, 2 mph.

Figure 15. Chassis Vertical Acceleration, 3-Inch Bump, 4 mph.

Comparing the chassis vertical accelerations of the MDARS and XUV models while the vehicles traversed the course at the 8- and 12-mph speeds showed a more significant difference between their respective acceleration amplitudes. The XUV model produced peak vertical acceleration amplitudes approximately 35% lower than did the MDARS model. Chassis vertical accelerations for the 8- and 12-mph comparisons are shown in Figures 16 and 17, respectively.
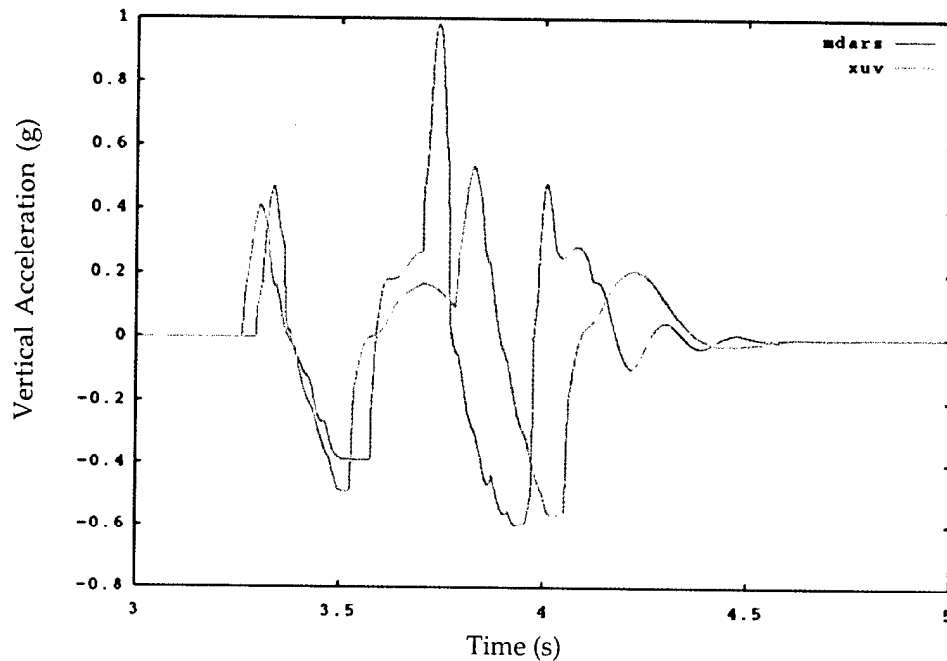

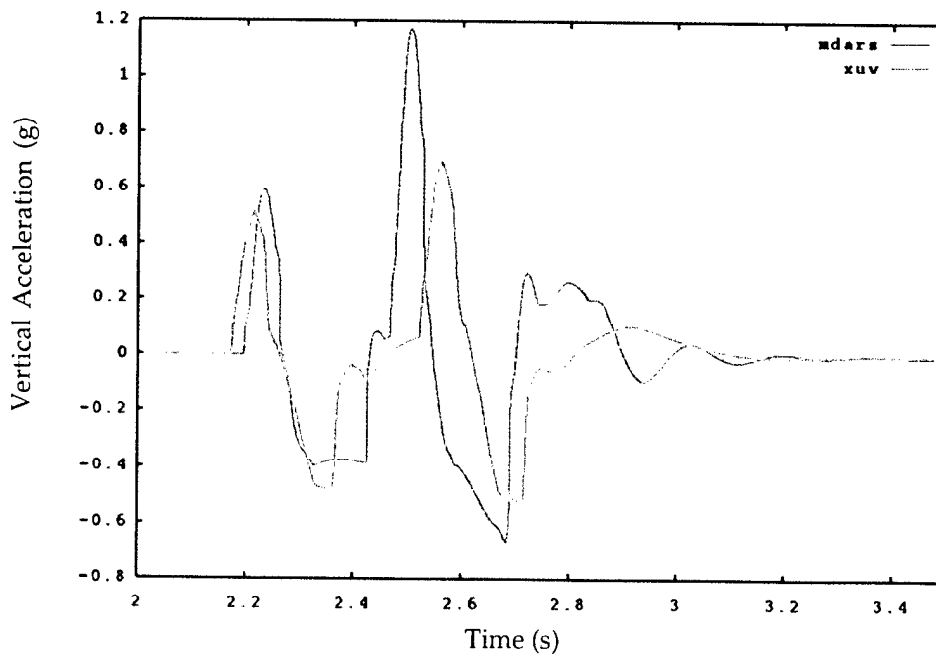Figure 16. Chassis Vertical Acceleration, 3-Inch Bump, 8 mph.

Figure 17. Chassis Vertical Acceleration, 3-Inch Bump, 12 mph.

Comparison of the chassis vertical accelerations between the MDARS and XUV models during the 18-mph run showed a continuing trend toward a larger difference in peak amplitudes. The XUV model produced peak vertical acceleration amplitudes approximately 45% lower than did the MDARS model while traversing the 3-inch bump course. Chassis vertical acceleration for the 18-mph comparison is shown in Figure 18.
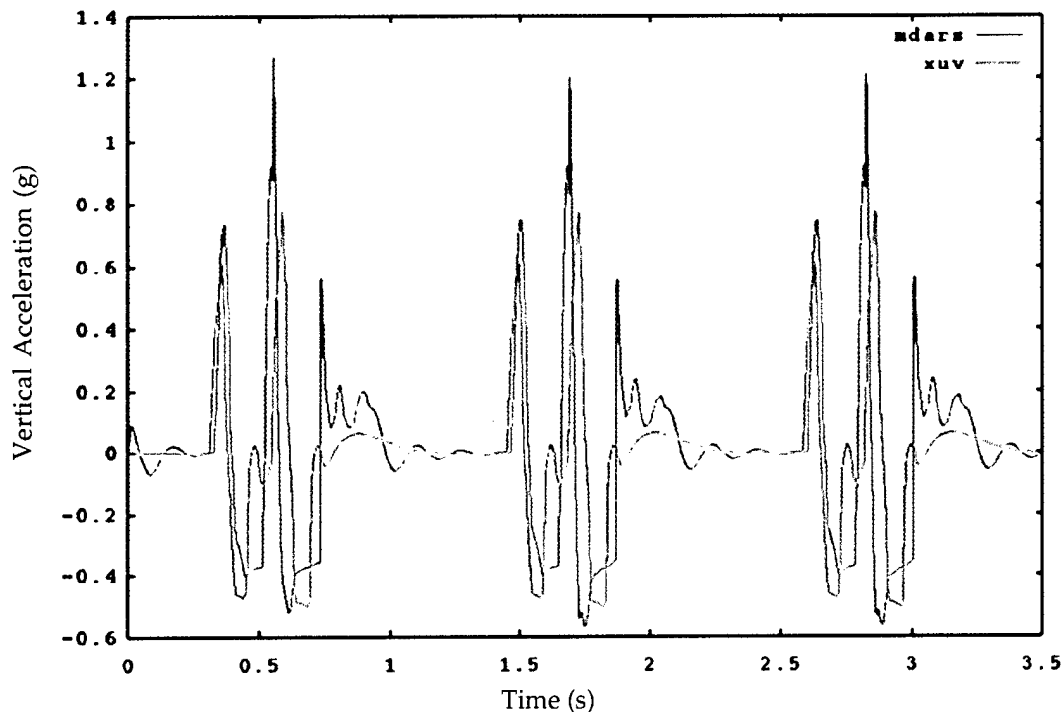

Figure 18. Chassis Vertical Acceleration, 3-inch bump, 18 mph.

3.2 MDARS Versus XUV Traversing the 2-inch Washboard Course

3.2.1 Pitch Rate Comparison

The MDARS and XUV simulation models were both run over the 2-inch washboard course at the same five speeds that were used for the 3-inch bump course comparisons. The 2-inch washboard course is basically a sinusoidal function with a 24-inch wavelength; thus, the pitch rate frequencies are clearly defined. For the speeds of 2, 4, 8, 12, and 18 mph, the pitch rate frequencies were 1.5, 3.0, 6.0, 9.0, and 13.5 Hz, respectively, showing that the simulation models exhibit a proper pitch rate frequency across the range of comparison speeds (see Figures 19 through 23). Comparison of the pitch rate amplitudes of the MDARS and XUV models while the vehicles traversed the 2-inch washboard terrain shows that the XUV model produces markedly lower pitch rate amplitudes than does the MDARS model. The XUV pitch rate amplitudes were

approximately 75% lower than the MDARS pitch rate amplitudes during the 2-mph comparison run. The 2-mph comparison is shown in Figure 19.
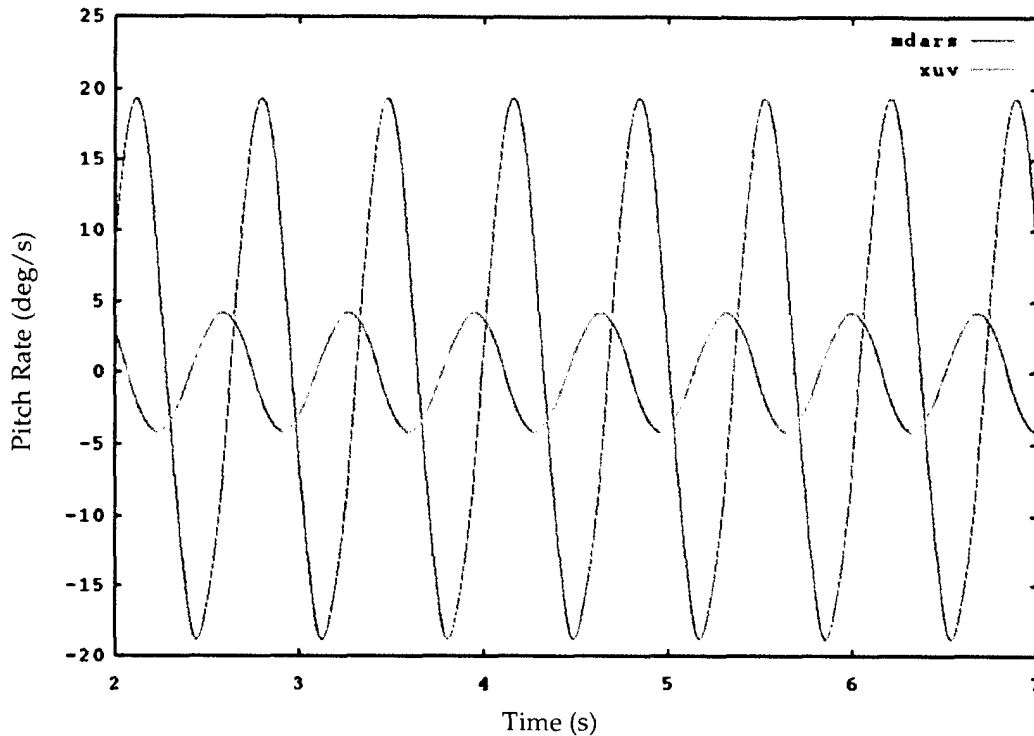

Figure 19. Chassis Pitch Rate, 2-Inch Washboard, 2 mph.

Comparison of the MDARS and XUV model pitch rate amplitudes during the 4- and 8-mph comparison runs shows that the XUV model produced pitch rate amplitudes approximately 80% lower than did the MDARS model. The 4- and 8-mph comparison runs are shown in Figures 20 and 21, respectively.

Examination of the 12- and 18-mph comparison runs between the MDARS and XUV models shows an even greater difference in their respective pitch rate amplitudes. The XUV model produces pitch rate amplitudes that are approximately 85% lower while the XUV traversed the terrain at the 12- and 18-mph speeds than did the MDARS model. The 12-mph comparison run is shown in Figure 22, and the 18-mph comparison run is shown in Figure 23.
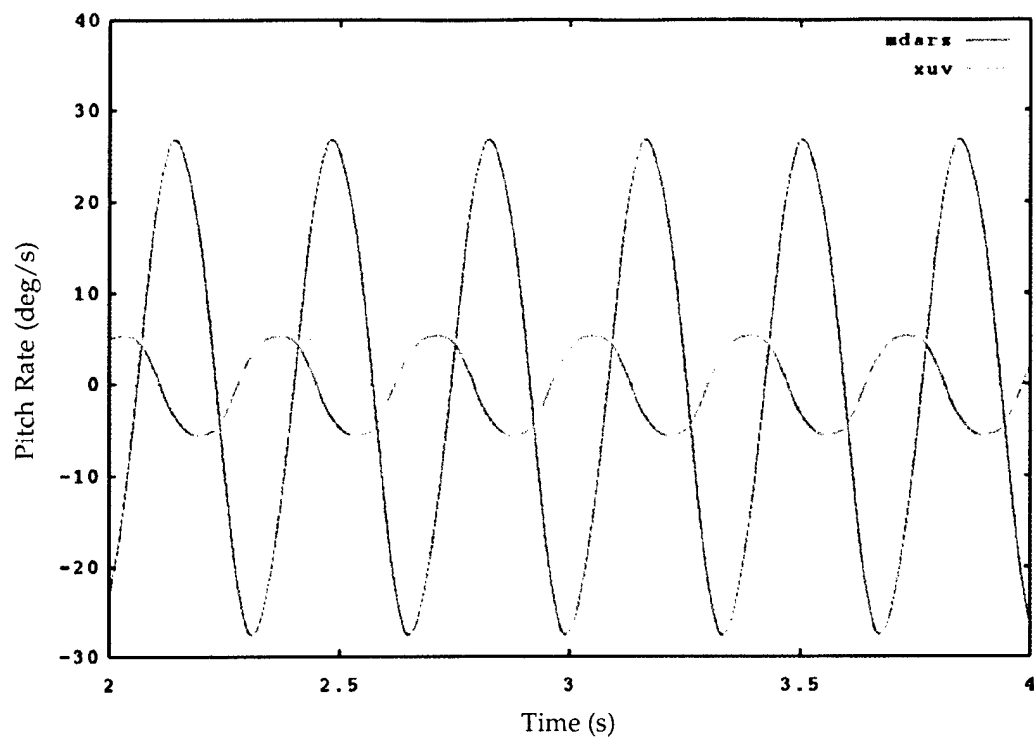
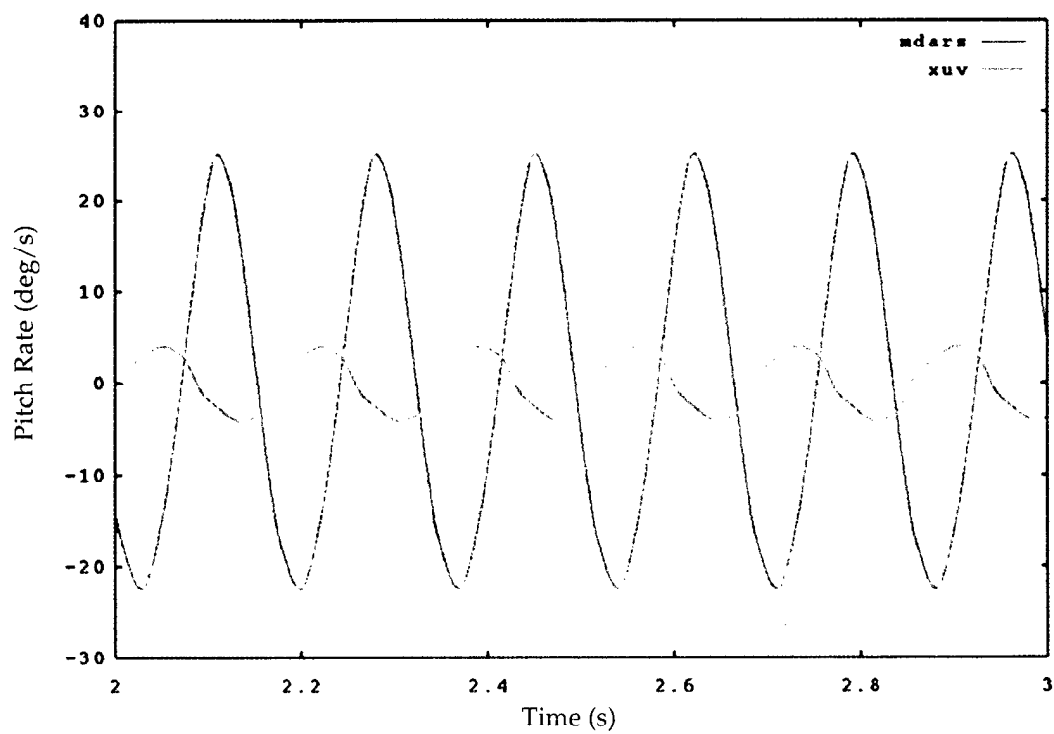Figure 20. Chassis Pitch Rate, 2-Inch Washboard, 4 mph.

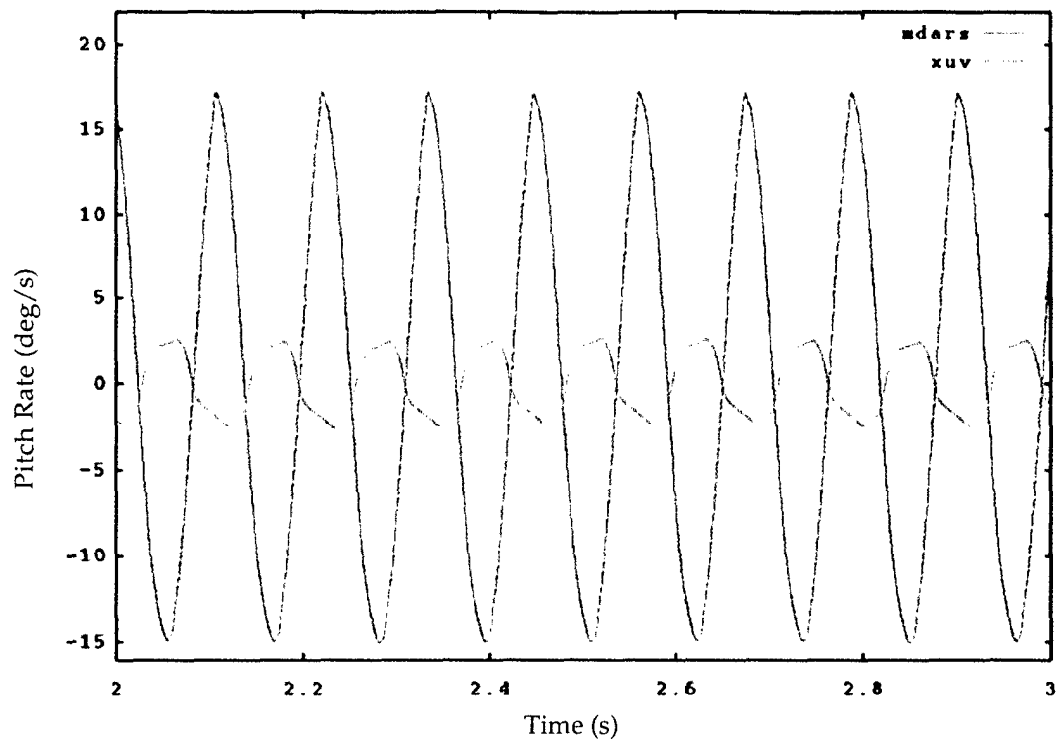Figure 21. Chassis Pitch Rate, 2-Inch Washboard, 8 mph.

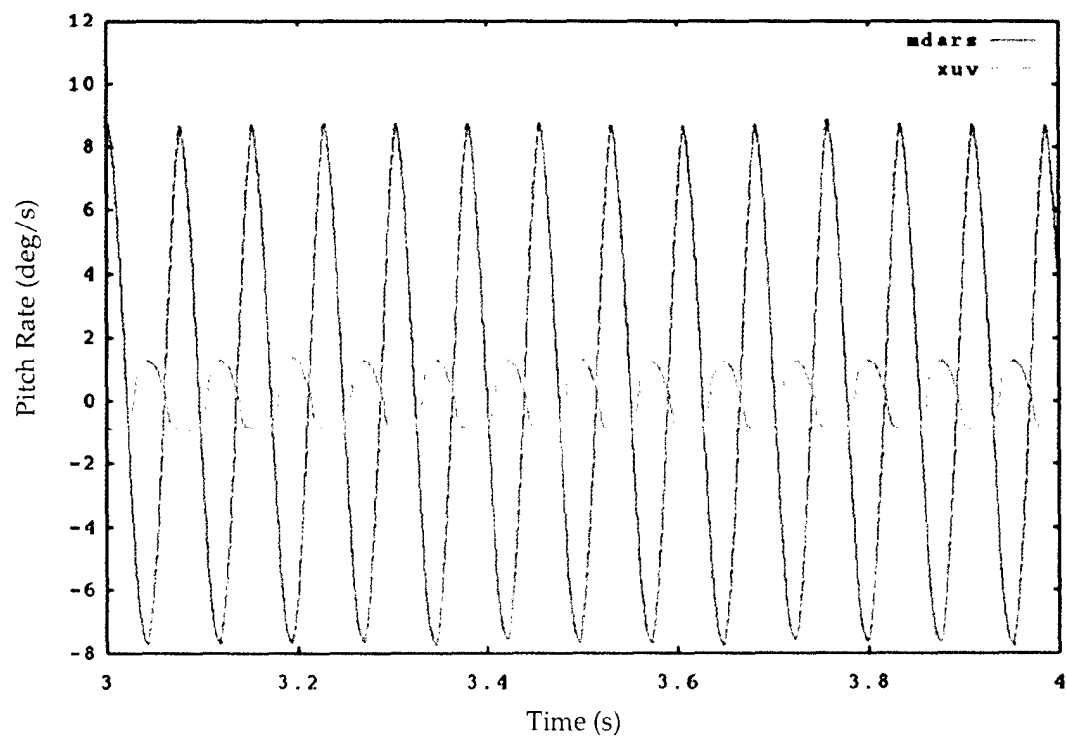Figure 22. Chassis Pitch Rate, 2-Inch Washboard, 12 mph.

Figure 23. Chassis Pitch Rate, 2-inch Washboard, 18 mph.

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3.2.2 Chassis Vertical Acceleration Comparison

The MDARS and XUV models were run over the 2-inch washboard course for the chassis vertical acceleration comparisons at the same speeds that were used for the pitch rate comparisons discussed before. Unlike the pitch rate and vertical acceleration comparisons for the 3-inch bump course, which both tended toward the XUV model having lower amplitudes than the MDARS model, the chassis vertical acceleration comparison on the 2-inch washboard course produced results that show the MDARS model exhibited lower peak vertical acceleration amplitudes than did the XUV model. These results most likely can be attributed to a resonant coupling between the washboard terrain wavelength and the XUV model's wheelbase length. This aspect is discussed in more detail in the discussion section of this report.

When the peak vertical acceleration amplitudes of the MDARS and XUV models were compared on the 2-inch washboard course at the 2-mph speed, it is clear that the MDARS model produced significantly lower amplitude levels. The MDARS model generated peak vertical acceleration amplitudes approximately 60% lower than did the XUV model. The 2-mph comparison is shown in Figure 24.
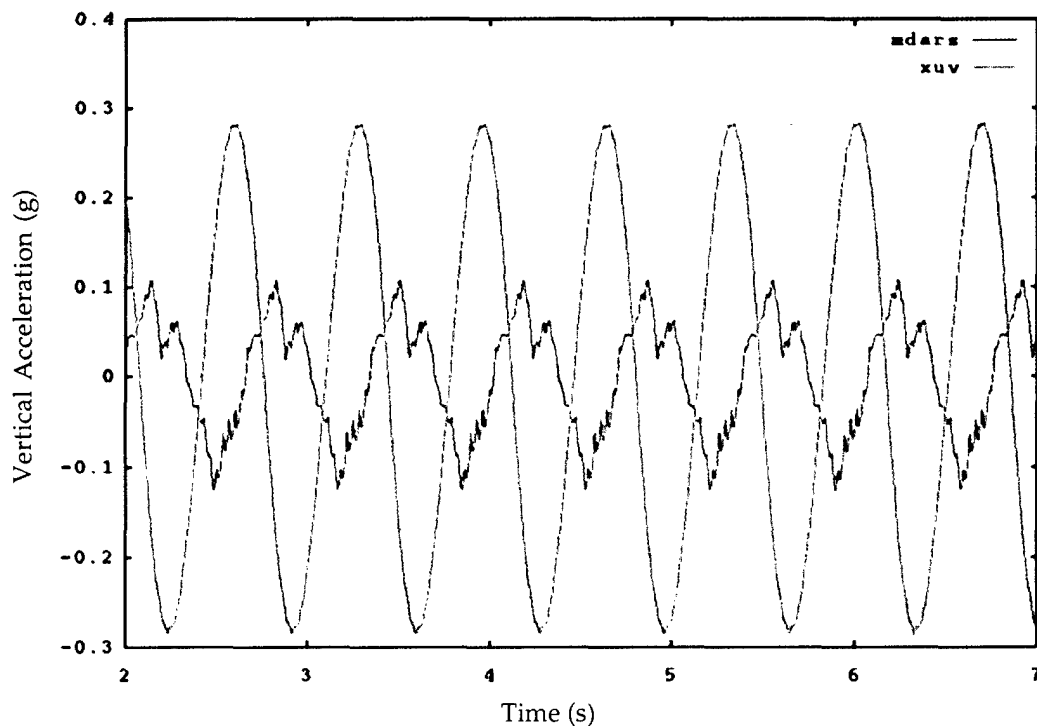

Figure 24. Chassis Vertical Acceleration, 2-Inch Washboard, 2 mph.

Comparison of the MDARS and XUV models during the 4-mph run shows that the MDARS model produced peak vertical acceleration amplitudes

approximately 30% lower than did the XUV model. The 4-mph comparison run is shown in Figure 25.

Figure 25. Chassis Vertical Acceleration, 2-Inch Washboard, 4 mph.

Examination of the peak vertical acceleration amplitudes during the 8-mph comparison run between the MDARS and XUV models shows a lessening difference between their respective amplitudes. The MDARS model produced peak vertical acceleration amplitudes approximately 15% lower than did the XUV model. The 8-mph comparison run is shown in Figure 26.

Comparison of the MDARS and XUV models during the 12- and 18-mph runs shows that the MDARS model again produced significantly lower peak amplitude levels. For both the 12- and 18-mph comparison runs, the MDARS model produced peak vertical acceleration amplitudes approximately 35% lower than did the XUV model. The 12- and 18-mph comparison runs are shown in Figures 27 and 28, respectively.
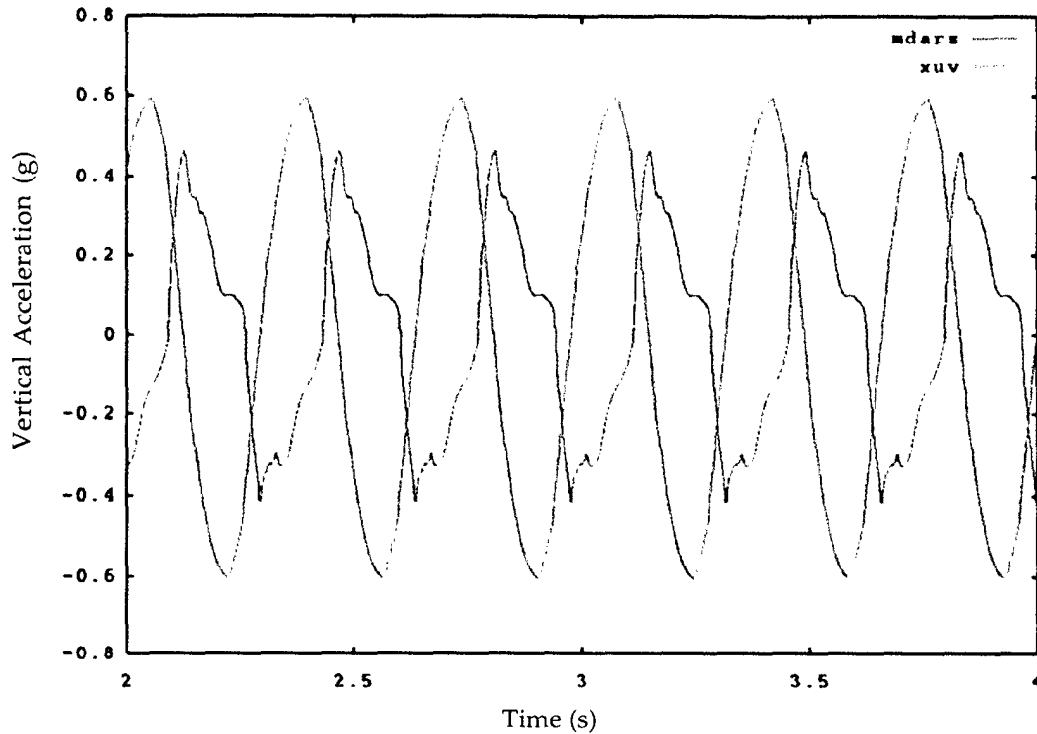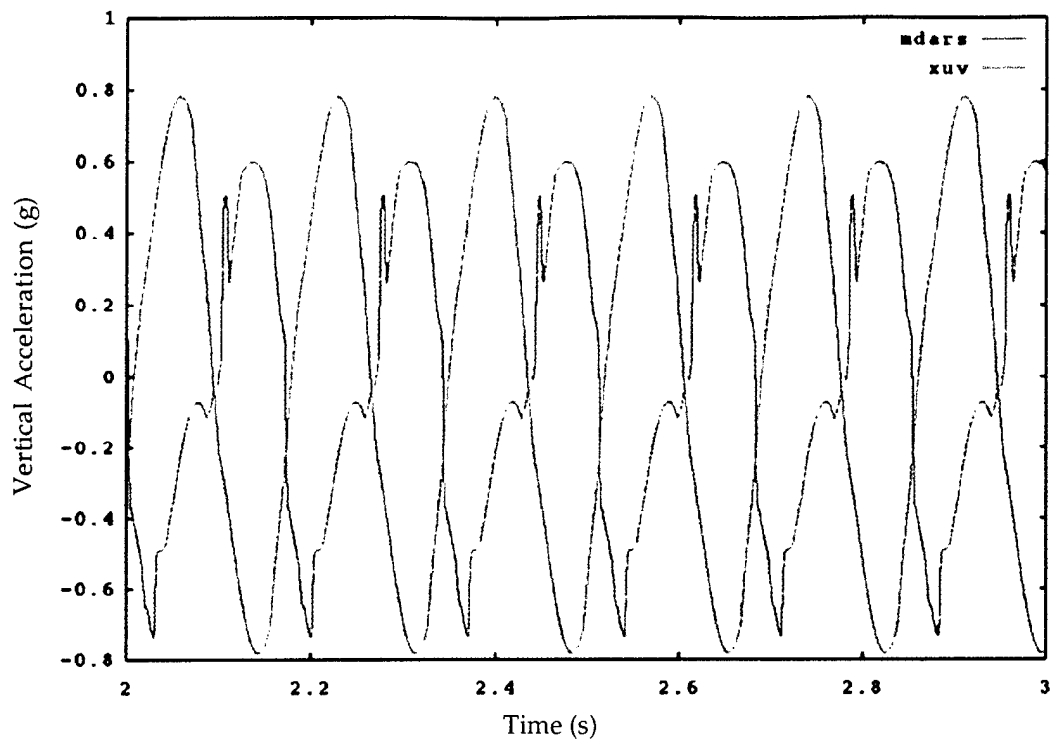
20

Figure 26. Chassis Vertical Acceleration, 2-Inch Washboard, 8 mph.
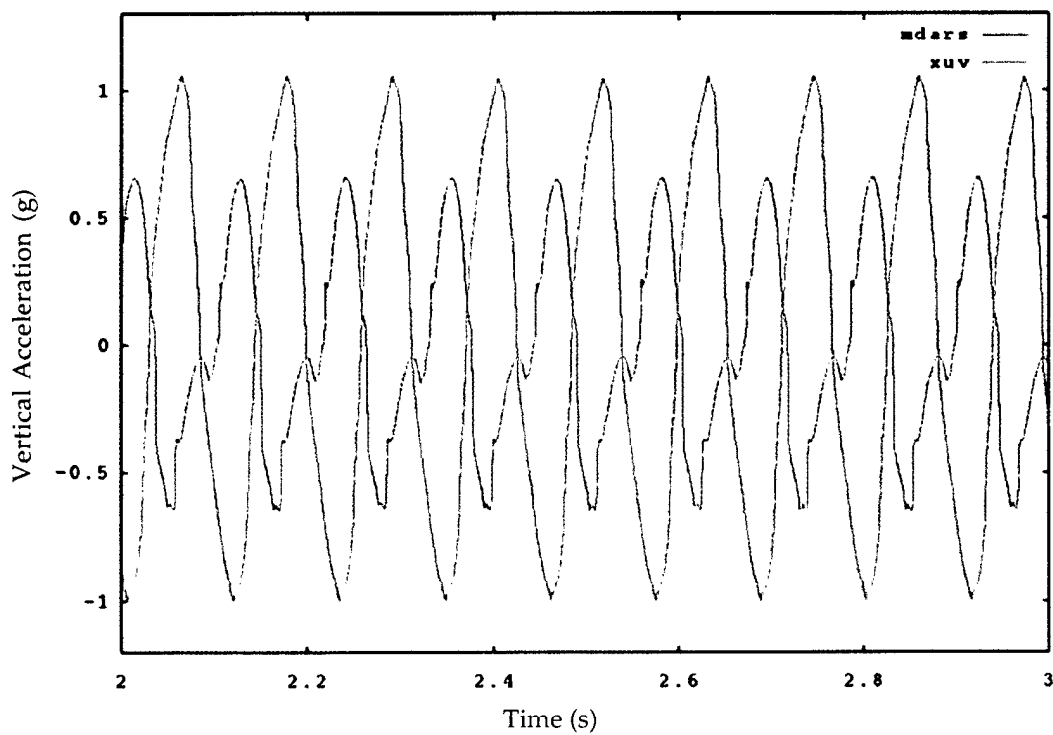

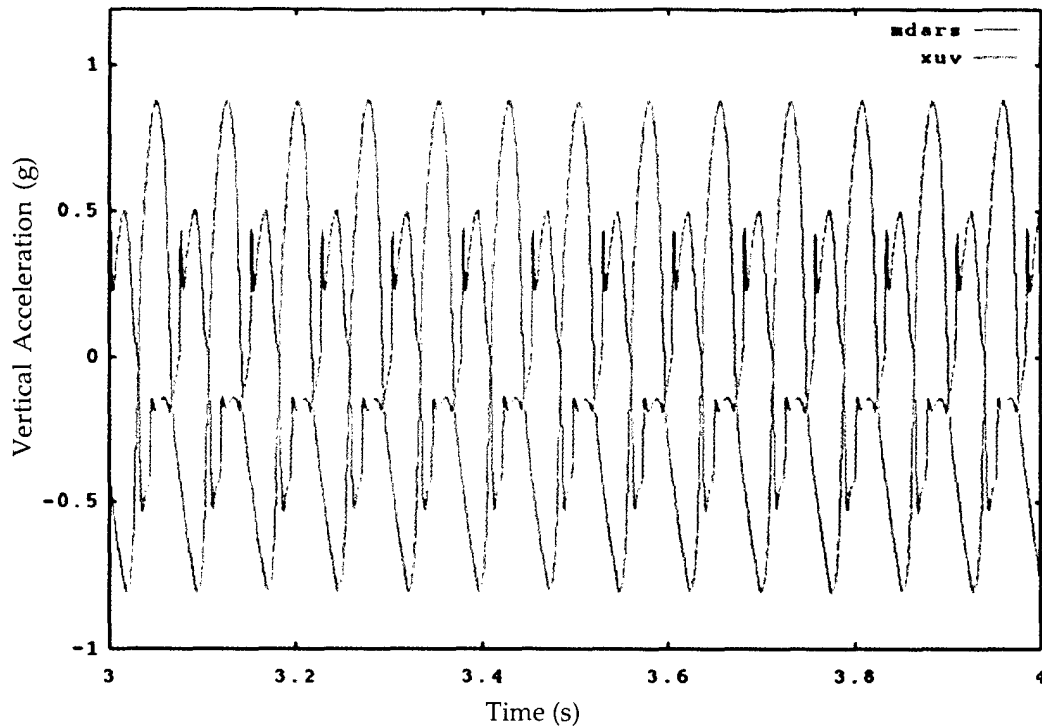Figure 27. Chassis Vertical Acceleration, 2-Inch Washboard, 12 mph.

Figure 28. Chassis Vertical Acceleration, 2-inch Washboard, 18 mph.

3.3 MDARS Versus XUV Traversing the WES T101 Terrain

3.3.1 Chassis Pitch Rate Comparison

The MDARS and XUV models were run over the WES T101 terrain at speeds of 2, 4, and 8 mph. The higher speeds of 12 and 18 mph, which were used in the comparison runs over the 3-inch bump and 2-inch washboard terrains, were not used in the comparison runs over the WES T101 terrain because the severity of the terrain caused extremely high pitch rate and vertical acceleration amplitudes to be generated by the MDARS model. These extreme amplitude levels indicated that the MDARS chassis that was modeled was being exercised beyond the vehicle's design limits. The WES T101 terrain does not have periodic bump spacing nor does it have regular and consistent bump height. The bump spacing and height of the T101 terrain are distributed in a more irregular manner, described as having a 1.5-inch rms bump height. Thus, the vehicle model's chassis response is also distributed in an irregular pattern. Within the data, regions with low amplitude levels exist, and other regions have very high amplitude levels.

Comparison of the MDARS and XUV pitch rate amplitudes over the T101 terrain at the 2-mph speed showed that the XUV model produced peak pitch rate amplitudes approximately 40% lower than those of the MDARS model. Comparison of the 2-mph run is shown in Figure 29.
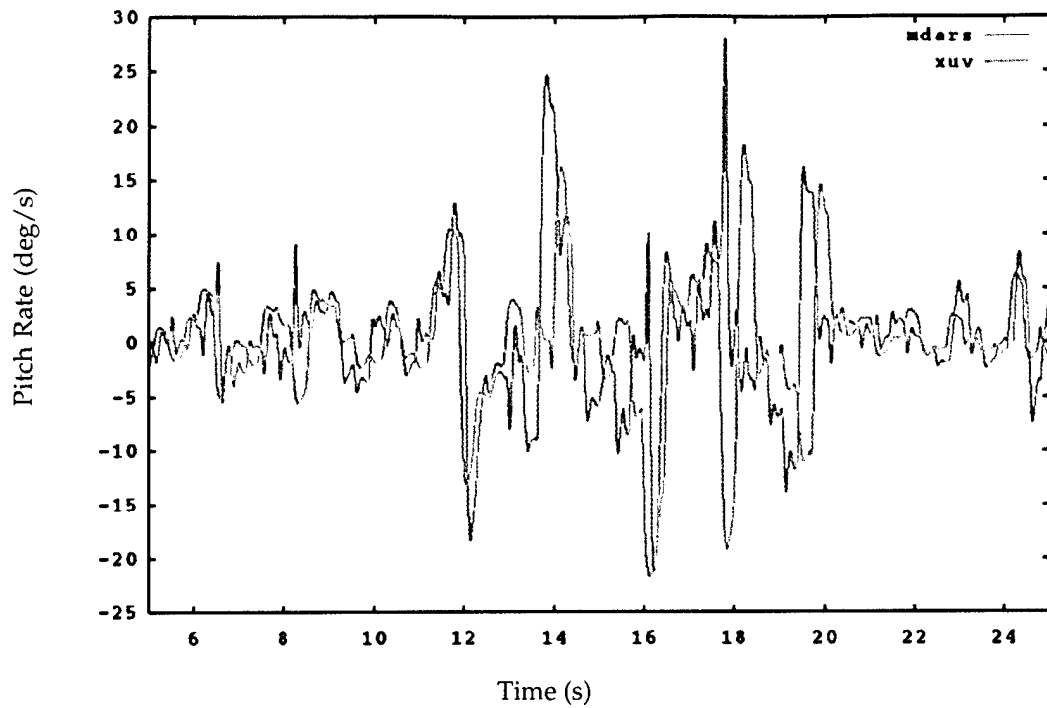
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Figure 29. Chassis Pitch Rate, T101, 2 mph.

Comparison of the MDARS and XUV model pitch rate amplitudes at speeds of 4 and 8 mph showed that the XUV had amplitude levels approximately 50% lower than did the MDARS model. The 4- and 8-mph comparison runs are shown in Figures 30 and 31, respectively.
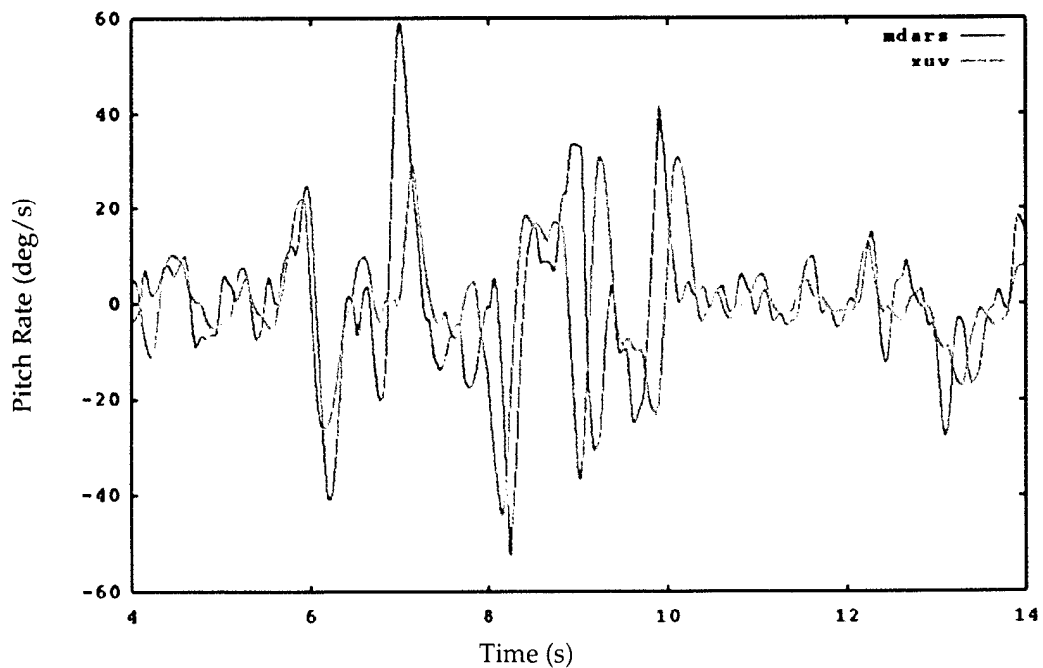

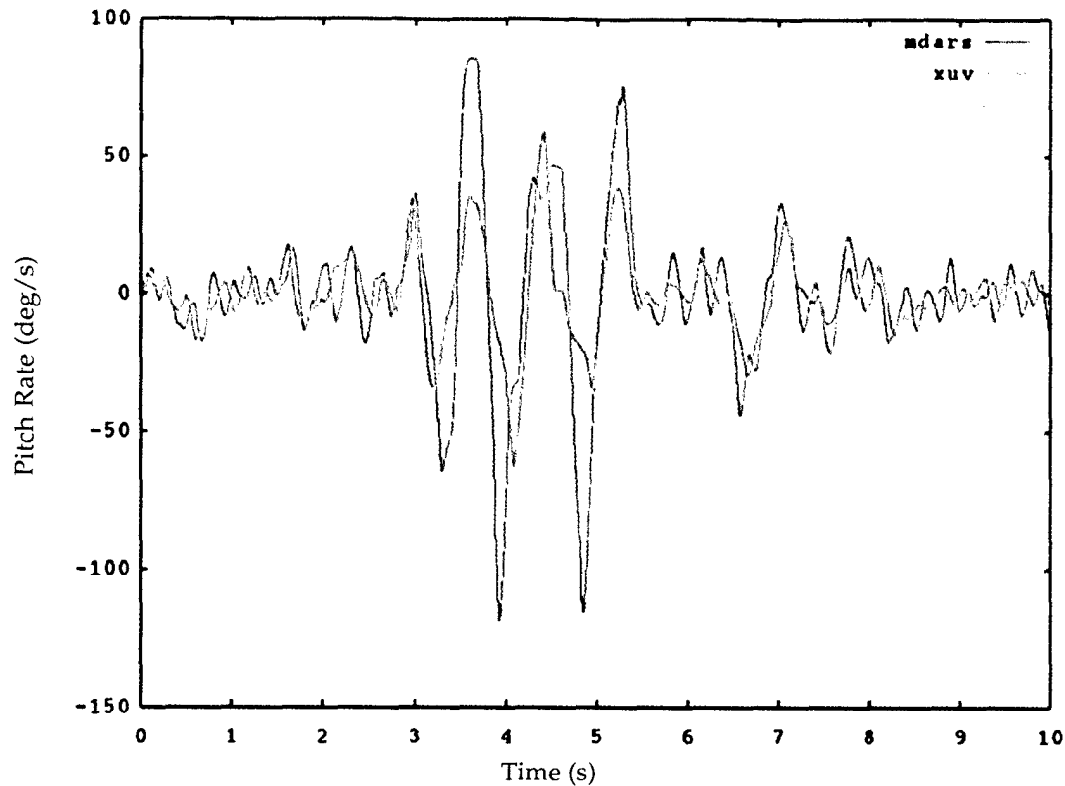Figure 30. Chassis Pitch Rate, T101, 4 mph.

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Figure 31. Chassis Pitch Rate, T101, 8 mph.

3.3.2 Chassis Vertical Acceleration Comparison

The comparison runs for the MDARS and XUV model chassis vertical accelerations over the WES T101 terrain were run at the speeds of 2, 4, and 8 mph. The 12- and 18-mph speeds were not used for the reason stated in Section 3.3.1. The MDARS and XUV models' chassis vertical acceleration amplitudes compared over the WES T101 terrain at the speeds of 2 and 4 mph showed that the XUV model exhibited peak vertical acceleration amplitude levels of approximately 30% to 40% lower than those of the MDARS model. The vertical acceleration comparisons for the 2- and 4-mph runs are shown in Figures 32 and 33, respectively.

The comparison of the MDARS and XUV models' chassis vertical acceleration amplitudes at the 8-mph speed showed a dramatic difference in peak acceleration levels. The XUV model exhibited a peak vertical acceleration amplitude approximately 75% lower than that of the MDARS model. While the MDARS traversed a particularly rough section of the T101 terrain, its model produced a peak vertical acceleration amplitude of nearly 4 g's, while the XUV model produced a level of about 1 g on the same course. Further, while running on that section of the terrain, both models produced an acceleration amplitude of –1 g, indicating that the vehicle models' tires had lost vertical contact with the terrain surface. Details of these events are further examined in Section 4.

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Comparison of the vertical accelerations during the 8-mph run is shown in Figure 34.
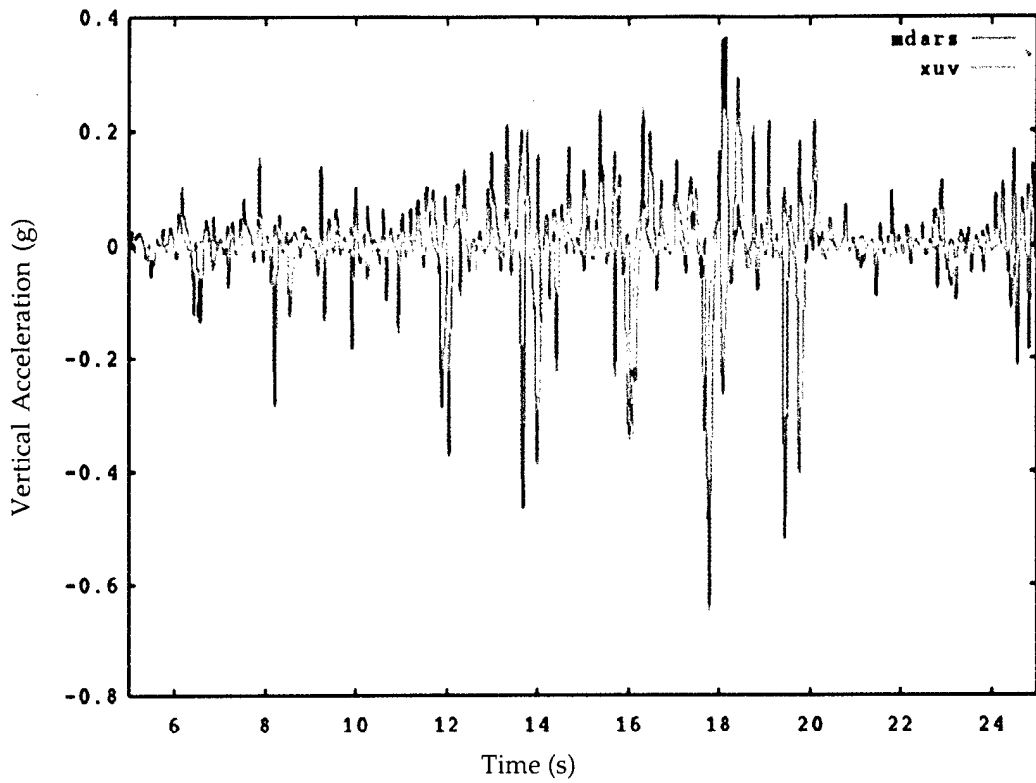

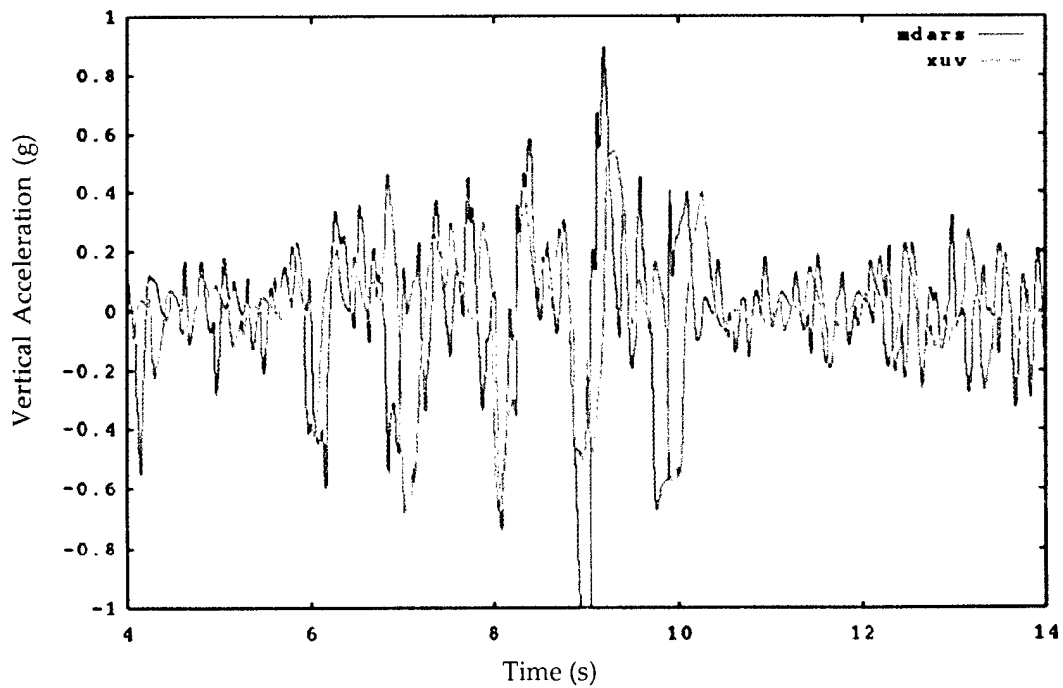Figure 32. Chassis Vertical Acceleration, T101, 2 mph.

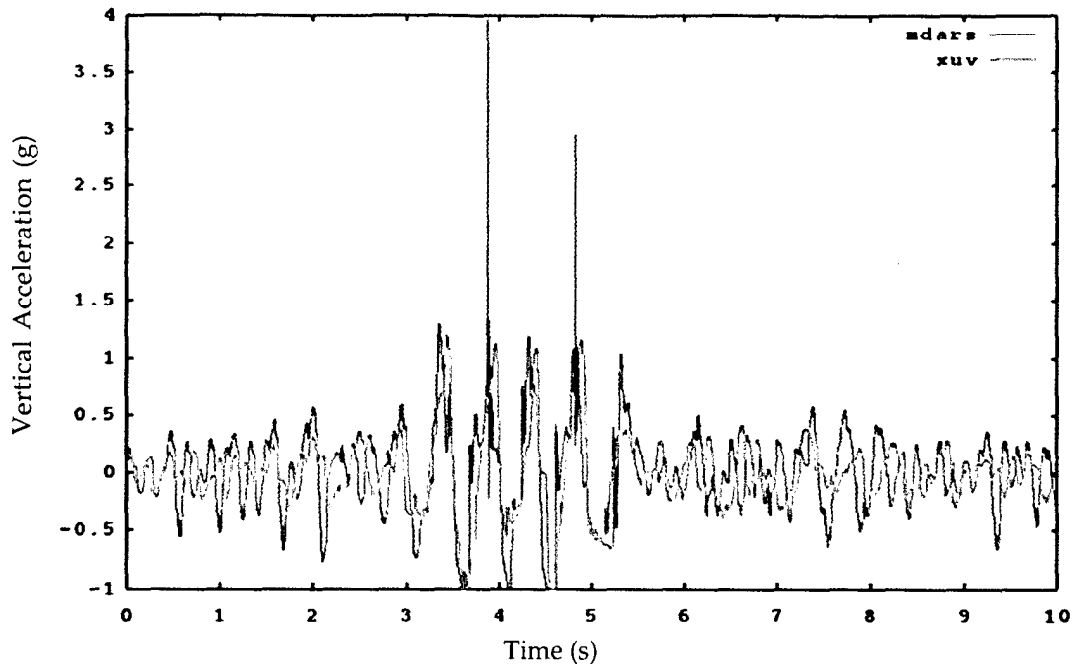Figure 33. Chassis Vertical Acceleration, T101, 4 mph.

Figure 34. Chassis Vertical Acceleration, T101, 8 mph.

4. Discussion

The results show that the comparisons between the MDARS and XUV models clearly exhibit the differences in their design structure. When the comparisons of the runs over the 3-inch bump course are reviewed for both the pitch rate and vertical acceleration amplitudes, the results show that the XUV model produced lower amplitude levels across the range of speeds. The differences between the peak amplitude levels for the MDARS and XUV models increase with progressively higher speeds. The lower amplitude levels produced by the XUV can be directly attributed to its having a longitudinal c.g. that is closer to the vehicle's wheelbase midpoint and to greatly increased suspension wheel travel. The XUV's longitudinal c.g. is approximately 50% closer to its wheelbase midpoint than is the c.g. of the MDARS. Reductions in pitch rate amplitudes are typically seen when a vehicle's longitudinal c.g. is moved closer to the vehicle's wheelbase midpoint. The MDARS has approximately 6 inches of front and rear suspension wheel travel, while the XUV has 10 inches of front and rear suspension wheel travel. Longer wheel travel relative to the vehicle's body tends to allow more of the bump energy to be absorbed before it is transmitted into the vehicle's chassis, thus producing lower levels of vertical acceleration.

When we look at the comparisons of the runs performed on the 2-inch washboard course, an interesting variation in the results is found. Comparison of the pitch rate amplitudes for the MDARS and XUV shows a trend similar to the

results of the 3-inch bump course comparison, wherein the XUV model produces consistently lower pitch rate amplitude levels. When the results of the vertical acceleration comparison are reviewed, a reversal in the trend is seen. While traversing the 2-inch washboard course at all speeds used in the comparison, the MDARS model had consistently lower levels of peak vertical acceleration amplitude than did the XUV model. These results are probably caused by an unintended resonant coupling between the terrain wavelength and the wheelbase length of the XUV model. The wheelbase length of the XUV is almost three terrain wavelengths long. This matching of the terrain wavelength and the vehicle's wheelbase length allows the vehicle's wheels to ride up and down in unison while traversing this periodic terrain. This "summing" of the front and rear suspension forces tends to produce larger vertical acceleration amplitudes than would typically occur when a vehicle's front and rear suspension is out of phase with the terrain features. Further, this phenomenon tends to suppress pitch motion. Therefore, the XUV model had significantly lower levels of pitch rate amplitude than did the MDARS model over this terrain.

When the comparisons of the MDARS and XUV models are reviewed while the vehicles traversed the WES T101 terrain, the results show that the XUV model produced lower peak levels of pitch rate and vertical acceleration amplitudes than did the MDARS model. This can be attributed to some of the factors mentioned previously, such as the XUV model's longitudinal c.g. being closer to its wheelbase midpoint and the XUV model having increased amounts of suspension wheel travel. Further, one other factor comes into play, especially while the vehicles traverse a more severe terrain such as the WES T101 terrain. The XUV model has a higher sprung-to-unsprung mass ratio. This ratio is the mass of the sprung components of the vehicle (essentially everything supported by the vehicle's springs) divided by the mass of the unsprung components (the wheels, tires, hubs, portions of the suspension control arms, etc.). A higher ratio tends to produce a vehicle with a suspension that reacts quickly to terrain perturbations, allowing the unsprung components to readily follow the terrain features, while letting the sprung mass travel along relatively unperturbed by the terrain features. The comparisons made on the WES T101 terrain only used speeds as great as 8 mph. Speeds above 8 mph caused extremely high levels of pitch rate and vertical acceleration amplitudes to be produced by the MDARS model. These high levels indicated that the MDARS model was being operated beyond its design limits. Looking at the vertical acceleration comparison over the WES T101 course run at 8 mph (see Figure 34), we see that the results show the MDARS produced very high levels of vertical acceleration (as great as 4 g's). Further, for both models, there are acceleration peaks showing −1 g, which indicate that the vehicles' wheels have lost vertical contact with the terrain surface. The XUV model produced relatively low vertical acceleration over this course, probably because of its extended wheel "jounce" travel, as compared to the MDARS vehicle model. The MDARS model, even at the 8-mph speed, was running against its design capabilities while it traversed the WES T101 course.

5. Summary

The comparison between the MDARS and the XUV simulation models traversing the 3-inch bump course, the 2-inch washboard course, and the WES T101 course clearly shows through the results that each model exhibits its design characteristics in a distinct fashion. The XUV model showed a clear advantage over the MDARS model in chassis pitch rate and vertical acceleration amplitude reduction for most of the courses at all speeds. The XUV model typically had lower levels of pitch rate and vertical acceleration amplitudes than did the MDARS model. These results can be attributed to the XUV chassis design having (a) a longitudinal c.g. closer to its wheelbase midpoint, (b) increased suspension wheel travel, and (c) a higher sprung-to-unsprung mass ratio. All these factors aid in reducing a vehicle's chassis pitch rate and chassis vertical acceleration amplitudes over a given terrain. One section of the results deviated from the trend of the XUV model having lower pitch rate and vertical acceleration amplitude levels. This occurred when the vertical acceleration amplitudes of the MDARS and XUV models were compared while the vehicles traversed the 2-inch washboard course. The MDARS model was found to have consistently lower levels of vertical acceleration amplitude than the XUV model. This is thought to be caused by an unintended resonant coupling between the terrain wavelength and the XUV model's wheelbase length. The XUV model's wheelbase length is almost three terrain wavelengths long. This tends to cause both front and rear wheels to rise and fall on the periodic terrain in unison. This causes a "summing" of the front and rear suspension forces, which produces higher vertical acceleration than would normally be produced when a vehicle's wheels are out of phase with the terrain features.

It is recommended that static and dynamic tests be performed on the XUV to collect actual data to verify that the correct engineering parameters have been used within the model and to validate the performance of the simulation model.

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Fazio, P.J., "Modeling of the MDARS Robotic Vehicle," ARL-TR-1991, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, July 1999.

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13. ABSTRACT (Maximum 200 words)

During fiscal years 1997 and 1998, the Weapons Analysis Branch, Ballistics and Weapons Concepts Division, Weapons and Materials Research Directorate of the U.S. Army Research Laboratory, built an engineering-level model of the unmanned ground vehicle platform used in the Office of the Secretary of Defense Demo III robotics program. The computer model was a representation of the mobile detection assessment reconnaissance system (MDARS) chassis-suspension system. The model was developed within the structure of the combat vehicle engineering simulation (CVES). This effort was undertaken to develop a simulation tool to evaluate the "ride quality" of small robotic vehicle platforms during off-road travel. "Ride quality" is defined as the ability of the vehicle's suspension to attenuate shock and vibration between the terrain surface and the vehicle chassis.

An ensuing effort was undertaken to develop a computer model of the second generation Demo III robotic vehicle, the experimental unmanned vehicle (XUV). This model was developed with engineering parameters and data provided by the vehicle's manufacturer within the structure of CVES. A simulated ride quality comparison study was performed on the MDARS and XUV chassis-suspension models. The two models were exercised over three different types of simulated terrain and five different speeds. The terrain types were digital representations of the Aberdeen Test Center 2-inch washboard course and 3-inch bump course and the Waterways Experimental Station (Vicksburg, Mississippi) T101 course. The data used for the comparisons were chassis pitch rates and vertical accelerations.

The results showed that the XUV model provided substantial reductions in pitch rate and vertical acceleration amplitudes when compared to the MDARS model over most terrain types at all speeds. Since these robotic vehicles perform autonomous driving, any reduction in pitch rate and vertical acceleration is desirable because of their adverse effects on the driving sensors.

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